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Fibrous cementitious material development for additive building manufacturing

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ABSTRACT

Additive Manufacturing (AM) in the construction industry is still in a relative state of infancy. Research has focused on heavy, ground based methods, with the building envelope determined by the dimensions of the deposition system. By comparison, the approach of using robots is not geometrically restricted but requires a degree of miniaturisation to the deposition process. Many studies utilise the AM principal of Fused Deposition Modelling (FDM), which creates an object by extruding a suitably viscous material through a nozzle and depositing one layer at a time. Crucial to the development of cementitious materials for Additive Building Manufacturing (ABM) without formwork, is the material possessing both workability and buildability, and appropriately balancing the contrasting requirements of these properties. Cementitious materials are typically brittle, requiring reinforcement to provide tensile and flexural capabilities. Reinforcing steel bars are not naturally compatible with ABM and chopped fibres are considered as a viable alternative. This paper investigates the development of a fibrous cementitious mortar suitable for use with a miniaturised deposition system based upon the FDM principal. Three types of fibres – Polypropylene, alkali-resistant glass and Polyvinyl Alcohol (PVA) - were investigated to assess workability, buildability, suitability for a miniaturised ABM deposition method and contributions to the mechanical strength of a mortar. PVA fibres provided the best buildability and increased flexural strength, with the appropriate quantity contained in mixes being informed by the negative impact upon workability.

1. Introduction

The construction industry has traditionally used formative or subtractive methods for building structures (Buswell et al. 2007), with freshly mixed material either being contained by supporting formwork or reduced to the size required from a bulk quantity. By contrast, the Fused Deposition Modelling (FDM) method of Additive Manufacturing (AM), better known as 3D printing, builds an object by extruding fresh material one layer at a time through a nozzle (Kalsoom et al. 2016), therefore only using the required amount of material and no formwork.

AM has much to offer the construction industry. By adopting an additive approach, material wastage can be reduced or even eliminated. Automating construction processes can improve productivity, reduce the risk of labour-related delays and improve the health and safety aspects of site construction in an inherently dangerous industry (Nadhim et al. 2016). Despite the potentially high costs of raw materials, additional savings can be made by integrating services into an AM construction project (Buswell et al. 2007). AM also offers the possibility of bespoke design at little extra cost, promoting a greater design and architectural freedom (Lim et al. 2012). However, when compared to the aerospace and automotive sectors, the use of AM processes in the construction industry is still in a relative state of infancy (Bos et al. 2016).

Previous studies using cementitious materials in Additive Building Manufacturing (ABM) have involved a large frame or gantry, the dimensions of which limit the size of the building envelope. Concrete printing, developed at Loughborough University, UK (Le et al. 2012), (Lim et al. 2012) and Contour Crafting, developed at the University of Southern California, USA (Zhang and Khoshnevis 2013) incorporate the FDM principal of slicing a 3D object into a series of layers and extruding material one layer at a time to create the object. An alternative approach to ABM is the use of moving robots in the deposition procedure, an example of which is the digital construction platform project developed at the Massachusetts Institute of Technology, USA (Keating et al. 2017). The use of robot technology, smaller in relation to large frames, would require the miniaturisation of the AM deposition process used.

Crucial to the success of FDM extrusion in the context of cementitious-based construction are the fresh properties of the material involved (Lim et al. 2012). A cementitious material must possess an appropriate balance between the identified material parameters of ‘pumpability’ (the ability of the material to progress through a deposition system), 'printability' (the level of ease at which the material may pass through a nozzle) and 'buildability' (the ability of the freshly deposited material to retain its shape upon deposition and accept loading from subsequently deposited layers) (Le et al. 2012). In this study, 'pumpability' and 'printability' will be combined into the general term 'workability'. There is a clear trade-off between workability, which requires liquid-like behavior and low viscosity, and buildability, which in contrast requires solid-like behavior and high viscosity.

When investigating the suitability of a cementitious material for ABM, a further consideration is that of ductility (Bos et al. 2017). With traditional cementitious-based construction methods, concrete is used with reinforcing steel bars, which provide the tensile and flexural capabilities of the material. When considering the use of robots in ABM deposition and the relative miniaturisation of the process required, steel reinforcing bars are not naturally compatible with the process and a viable alternative option must be sought to provide an element of ductility to the cementitious material matrix. This paper focuses upon the use of chopped fibres within a cementitious mortar mix suitable for the FDM method in a miniaturised ABM process. Polypropylene (PP), 17%+ zirconia Alkali-Resistant Glass (ARG) and Polyvinyl Alcohol (PVA) fibres are of a suitable size to be added to a cementitious material and pass through a miniature deposition system. Fibrous mortar mixes are assessed, in varying quantities, for their workable, buildable and mechanical properties along with the ability of the fibres to mitigate crack propagation when subject to tensile forces, and the mechanism (pull-out or rupture) of fibre failure.

2. Materials and Methodology

Fibre volume fraction affects the properties of hydrated cementitious materials. Fibrous concrete with a low volume fraction (0.1-1%) has been used for controlling plastic shrinkage, whereas high fibre volume fraction concrete improves mechanical properties and crack resistance. However, high volume fraction materials present challenges regarding workability (Noushini et al. 2014). Fibres were therefore added in at low volume fractions in order to maintain workability through a miniature syringe-based deposition system. The geometrical properties of the PP, ARG and PVA fibres used in this study are presented in Table 1.

Table 1. Properties of the PP, ARG and PVA fibres.

	LENGTH	DIAMETER	DENSITY
	(mm)	(microns)	(g/cm^3)
PP	12	40	0.9
ARG	13	580	2.7
PVA	19	350	1.3

Ten different mixes were formulated, comprising a control mix - which contained no fibres - and three mixes of each fibre (PP, ARG and PVA) at 1.2 kg/m^3, 2.4 kg/m^3 and 3.6 kg/m^3 quantities as shown in Table 2. The cementitious matrix for the test specimens was based upon Dragon Alfa CEM I 42.5 R Portland cement, augmented by Cemex PFA EN-450 in a respective ratio of 65:35. Adoflow 'S' plasticiser was used to aid workability, and a fine aggregate formed of kiln-dried building sand with a maximum particle size of 2 mm was added. Coarse aggregate was not used due to being incompatible with the miniaturised deposition system. A sand/binder ratio of 1:1 (to facilitate the required workability), water/binder ratio of 0.44 and superplasticiser content of 1% by mass of binder were kept consistent throughout the mixes. Mechanical test specimens were cast in 160 mm x 40 mm x 40 mm prisms, cured and tested in accordance with BS EN 1015-11:1999 at both 7 days and 28 days to attain compressive and flexural strengths using an Instron Universal 2630-120/305632 machine.

Workability and buildability of the fresh mixes were evaluated using a miniature syringe-based deposition device capable of drawing up and extruding the material. The device consisted of one 60 ml concentric luer-loc syringe, with plunger movement in both directions actuated by a powered miniature 6V DC brushed motor (Dams et al. 2017). Each mix detailed in Table 2 was drawn up using the syringe device and extruded from the syringe in circular layers through an 8mm diameter circular nozzle. Workability was evaluated on the level of ease at which the device could draw up and extrude the material, quantified by the electrical current used (also shown in Table 2). Buildability was evaluated by the number of cohesive extruded layers produced and by inspection, the ability of the material to retain its shape upon deposition and respond to the weight of subsequently extruded layers without deformation leading to instability.

Table 2. Mixes with volume fractions and the range of current required for intake and extrusion by the syringe deposition device. Mixes PP 3.6 and PVA 3.6 were the least workable and could not be processed by the deposition device (indicated as NP).

Mix	Fibre volume Fraction	Current required
	(%)	(mA)
Control	-	58-63
PP 1.2 kg/m^3	0.11	65-75
PP 2.4 kg/m^3	0.22	70-91
PP 3.6 kg/m^3	0.33	NP
ARG 1.2 kg/m^3	0.07	58-66
ARG 2.4 kg/m^3	0.14	60-68
ARG 3.6 kg/m^3	0.21	60-66
PVA 1.2 kg/m^3	0.04	59-77
PVA 2.4 kg/m^3	0.08	65-81
PVA 3.6 kg/m^3	0.12	NP

The failure mode of extruded cement-fibre composites is dependent on the critical fibre length. Fibre pull-out will take place when the average fibre length provided in the mix design is less than the critical fibre length. Depending on the fibre/matrix interfacial strength, fibre rupture will occur as a primary failure mode if the average fibre length is longer than the critical length (Koker and Zijl 2004). The surface morphology of the different fibres included in this study and also the fracture surface of the specimens following mechanical testing (at 28-day strength) was investigated using a JEOL SEM6480LV Scanning Electron Microscope. Magnifications of 1000x and 43x were used for the bare fibres and the fracture surfaces respectively. A 10 nm coating of gold was sputtered onto to the samples immediately prior to insertion into the microscope chamber to prevent charging and increase signal-to-noise ratio. Fibrous specimens were also examined by inspection upon completion of flexural strength tests.

3. Results and Discussion

Figure 1 illustrates the 7-day and 28-day compressive (top) and flexural strengths (bottom) of the fibrous and fibre-free control mixes. ARG and PVA fibre mixes remained competitive with the fibre-free control mix with regards to compressive strength and both ARG and PVA fibres improved flexural strength and provided resistance to crack propagation.

Figure 2 shows modes of failure following flexural strength tests. The control mix exhibited brittle failure with the specimen fully splitting into two (a), while fibres aided resistance to crack propagation (b). PP fibres failed by pull-out (c) and ARG fibres failed by rupturing (d). PVA fibres observed failed by rupture and pull-out. PVA and ARG fibres possess higher tensile strength than PP fibres, resulting in a higher flexural strength in the mortar material, but the pull-out failure mechanism of PP fibres displays the most ductile behaviour. All three fibres provided resistance to crack propagation and prevented the specimen from breaking cleanly into two.

Figure 3 displays SEM images of the fibres (a-c) and fibres contained within the cementitious mortars, post-flexural testing (d-f). The PP fibres have a smooth appearance (a), the ARG fibres consist of groupings of silica strands with a void clearly visible (b) and the PVA fibres have a notably rougher surface with a hook-like feature visible (c). A void is indicated to the top-right PP specimen image (d), where PP fibres have been pulled out of the mortar matrix during the flexural tests, whereas (e) and (f) show ruptured ARG fibre strands and a PVA fibre respectively.

It can be reasoned that PP is more prone to pull-out because the smooth surface of the fibre strands is not conducive to providing good anchorage within the mortar matrix. Conversely, the less smooth surfaces of ARG and PVA with its hook-like features, provide stronger anchorage within the mortar, minimising the risk of pull-out and encouraging failure by fibre rupture.

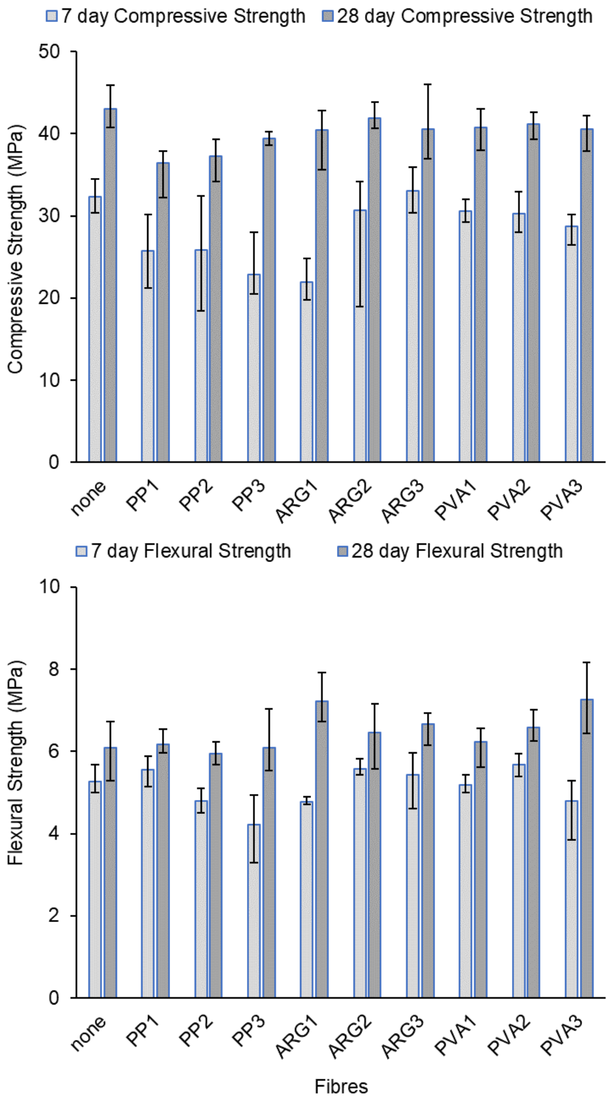

Figure 1. 7-day and 28-day compressive (top) and flexural (bottom) strengths of the mixes. 1, 2 and 3 refer to the 1.2, 2.4 and 3.6 kg/m^3 fibre fractions in the respective mortar mixes (shown in Table 2). ‘none’ indicates the fibre-free control mix.

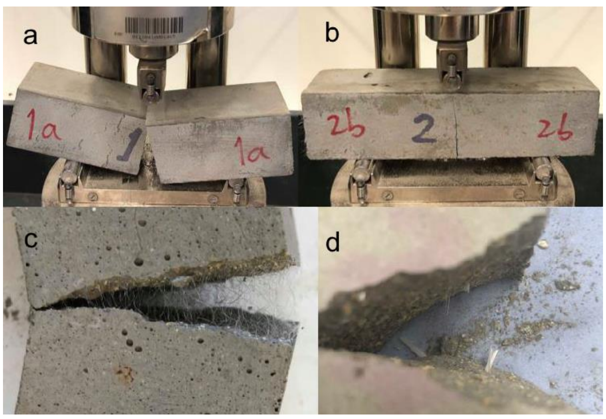

Figure 2. Modes of failure, (a) prism without fibres breaking into two (b) PP specimen resists crack propagation (c) PP fibre failure mechanism (pull-out) and (d) ARG fibre failure mechanism (ruptured fibre strands).

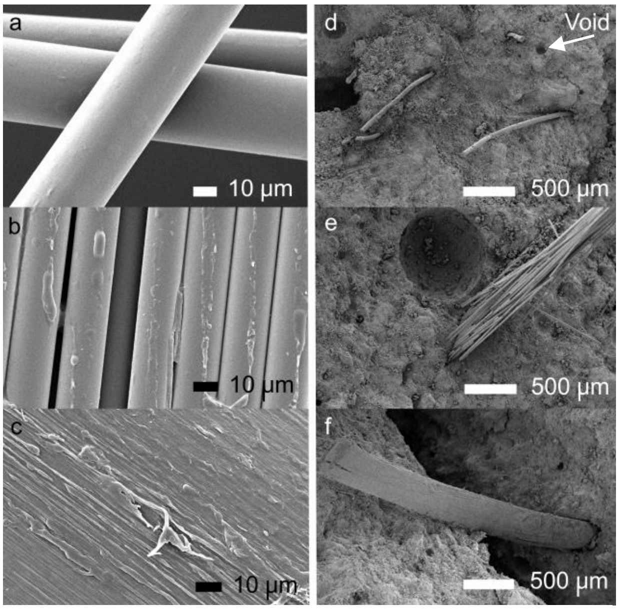

Figure 3. SEM images of the fibres prior to testing (a-c) and broken fibres within cementitious matrices, post 28-day flexural strength tests (d-f). Images a-c were at x43 magnification, d-f at x1000 magnification. (a,d) PP, (b,e) ARG and (c, f) PVA. A void is visible in (d), the result of a PP fibre failing by pull-out.

As expected, the inclusion of all three fibres detracted from workability but aided buildability. Shown in table 2, as fibre concentration increases, the amount of power required to draw-up and extrude the mix increases. However, without fibres, extruded circular layers quickly became unstable under their own weight and collapsed when subjected to subsequent layers – whereas fibre addition aided layer stability. Figure 4 shows extruded samples of fresh mixes without fibres ('control mix') (a), PP1.2 (b), ARG1.2 (c) and PVA1.2 (d), with PVA fibres providing the most coherent and stable extruded layers. With mix PVA2.4, 6 stable layers were achieved (the highest quantity, thus highest buildability), while 5 stable layers were achieved with PP2.4, ARG2.4 and ARG3.6. This contrasts with the high workability, low buildability control mix (unstable after the fourth layer) and PP1.2 (unstable after the fifth layer).

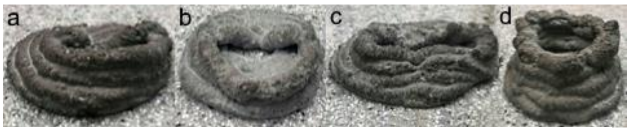

Figure 4. Buildability tests with circular layers extruded from the syringe device, (a) control mix (b) PP1.2 (c) ARG1.2 and (d) PVA1.2. PVA fibres provided the most buildable mixes.

4. Conclusions and further work

Adding fibres to an ABM mortar mix aids buildability but detracts from pumpability and printability. Mortar with 2.4 kg/m^3 PVA fibre content is the most suitable mix investigated in this study for the miniaturised ABM deposition system. It possesses an appropriate balance between workability and buildability, with competitive flexural and compressive strengths (7 MPa and 40+ MPa respectively) and remains extrudable at 2.4 kg/m^3 fibre content, requiring less current to process than the equivalent PP mix. Fibre mixes containing 3.6 kg/m^3 present workability issues for a miniature system. The uneven surface of PVA fibres, containing hook-like features, enables good anchorage in the mortar matrix and aids flexural strength. However, a drawback is the risk of the less ductile failure mechanism of fibre rupture. Further work would examine fibre orientation - how this is influenced by extrusion and the effects of anisotropy upon buildability and flexural strength - along with the development of a miniature deposition system with a larger syringe and more powerful motor capable of processing a mortar mix containing a fibre volume fraction of up to 2%, high enough to be a substitute for reinforcing steel bars.

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